(12) LEVEL II

MISCELLANEOUS PAPER EL-81-4

INCLUSION OF A SIMPLE VEGETATION LAYER IN TERRAIN TEMPERATURE MODELS FOR THERMAL INFRARED (IR) SIGNATURE PREDICTION

by

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AD A104469

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August 1981

Final Report

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Prepared for Headquarters, Department of the Army
Washington, D. C. 20314

Under Project No. 4A762730AT42, Task A4, Work Unit 003 and
Project No. 4A762719AT40, Task CO, Work Unit 006

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(14) WES/MP/EL-81-4

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Miscellaneous Paper EL-81-4	2. GOVT ACCESSION NO. AD-A104469	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) INCLUSION OF A SIMPLE VEGETATION LAYER IN TERRAIN TEMPERATURE MODELS FOR THERMAL INFRARED (IR) SIGNATURE PREDICTION.		5. TYPE OF REPORT & PERIOD COVERED (9) Final report. 1 Oct 79-10 ...
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) Lee K./Balick Randy K./Scoggins Lewis E./Link, Jr		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Environmental Laboratory P. O. Box 631, Vicksburg, Miss. 39180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project No. 4A762730AT42, Task A4, Work Unit 003, and Project No. 4A762719AT40, Task CO, Work Unit 006
11. CONTROLLING OFFICE NAME AND ADDRESS Headquarters, Department of the Army Washington, D. C. 20314	17/A4, 20	12. REPORT DATE (11) Aug 1981
		13. NUMBER OF PAGES 39 (12) 44
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) (16) 4A762730AT42, 4A762719AT40		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Available from National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22151.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Computerized simulation
Infrared detectors
Temperature
Terrain analysis
Terrain models (Analytical)
Thermal measurements
Vegetation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Thermal infrared signatures of natural and cultural features are dynamic, varying with time and weather conditions. Prediction of thermal signatures for specific conditions requires first that the actual temperature of the features be determined; for vegetation canopies this involves the average temperatures of canopy components and for planar (nonvegetated) surfaces the temperature of the surface. Models have been developed to handle layered vegetation canopies and layered ground surfaces; however, efforts have only begun to (Continued)

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20. ABSTRACT (Continued).

formulate a comparable capability for intermediate conditions such as grass covered surfaces where both the terrain surface and vegetation influence the average surface temperature.

This report presents a procedure, named VEGIE, that predicts the temperature of terrain surfaces which contain a simple layer of vegetation. VEGIE is designed as an interim procedure for immediate application in lieu of more sophisticated and theoretical treatments of this problem. Operational flexibility and simplicity are preserved by using VEGIE as a submodel to the Terrain Surface Temperature Model (TSTM) developed previously at the U. S. Army Engineer Waterways Experiment Station. The TSTM predicts the surface temperature of nonvegetated layer and planar features using material thermophysical properties and meteorological conditions.

The frameworks of the TSTM and VEGIE are presented along with the strategy for their joint application to temperature predictions for simply vegetated surfaces. The sensitivity of the temperature predictions to the inputs required by VEGIE are examined to assist in determining the limits of its validity. A limited validation is presented using measured data for a site in West Germany. Results from VEGIE are also compared to the output of a more sophisticated (and complete) vegetation temperature model developed at the Colorado State University (CSU).

These models are applied to a deciduous and a coniferous canopy where the CSU model is valid but VEGIE is not. VEGIE is applied to the problem of estimating thermal signatures for terrain surfaces with less than total foliage cover, the consequences of changes in foliage cover, differing emissivities for the soil and vegetation, and reflected sky radiation.

The data and analyses presented herein demonstrate that the simplified treatment of energy budgets used in VEGIE provide realistic results for the situations that VEGIE was designed to handle. Under some conditions, when sun and view geometry are important or where canopies have large horizontal variations to outline a few, the results from VEGIE may be of limited value. VEGIE would appear to perform well in moderate environmental situations such as lawns, pastures, and rangelands.

PREFACE

The study reported herein was conducted by personnel of the U. S. Army Engineer Waterways Experiment Station (WES) from 1 October 1979 to 1 October 1980. The study was done under Department of the Army Projects No. 4A762730AT42, Task A4, Terrain/Operations Simulation, Work Unit 003, Electromagnetic Target Surround Characteristics in Natural Terrains, and No. 4A762719AT40, Task CO, Theater of Operations Construction, Work Unit 006, Fixed Installation Camouflage Methods and Materials.

The study was conducted under the general supervision of Dr. John Harrison, Chief of the Environmental Laboratory, and Mr. Bob Benn, Chief of the Environmental Systems Division, and under the direct supervision of Dr. Lewis E. Link, Jr., Chief of the Environmental Constraints Group (ECG). The development of the mathematical model presented herein was accomplished primarily by Dr. Lee Balick, on assignment to ECG from Colorado State University (CSU). Assistance was received from Messrs. Randy Scoggins and Curt Gladen, ECG. This report was prepared primarily by Dr. Balick with technical assistance from Dr. Link and Mr. Scoggins, and administrative assistance from Ms. Patti Burke.

Forest canopy thermal signature and model data were obtained with the collaboration of Dr. Leo J. Fritschen (College of Forest Resources of the University of Washington, Seattle, Wash.), Dr. Boyd A. Hutchison (Atmospheric Turbulence and Diffusion Laboratory, National Oceanic and Atmospheric Administration, Oak Ridge, Tenn.) and Dr. James A. Smith (Department of Forest and Wood Science, CSU, Fort Collins, Colo.). In addition to their scientific collaboration, Drs. Fritschen and Hutchison were hosts of field experiments at their research sites which were cooperative efforts between their organizations, CSU and WES. Dr. Smith led the development of the CSU thermal model, which provided temperature predictions for the grass and forest canopies.

Commanders and Directors of the WES during the conduct of the study were COL John L. Cannon, CE, and COL Nelson P. Conover, CE. Technical Director was Mr. Fred R. Brown.

This report should be cited as follows:

> Balick, L. K., Scoggins, R. K., Link, L. E., Jr. 1981. "Inclusion of a Simple Vegetation Layer in Terrain Temperature Models for Thermal Infrared (IR) Signature Prediction," Miscellaneous Paper EL-81-4, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

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INCLUSION OF A SIMPLE VEGETATION LAYER IN TERRAIN TEMPERATURE MODELS FOR THERMAL INFRARED (IR) SIGNATURE PREDICTION

PART I: INTRODUCTION

Background

1. Recent analytical and theoretical studies of the thermal infrared (IR) emission characteristics of terrain surfaces have generally ignored the effects of vegetation on thermal IR signatures (Gillespie and Kahle 1977; Pratt and Ellyett 1979; Holmes, Nuesch, and Vincent 1980). This seems to be due, in part, to a lack of a usable tool for examining the effects of vegetation in a real world. In truth the problem is very complex. Models of vegetation temperature which can be directly applied to remote sensing problems (Kimes, Smith, and Ranson 1979; Norman, 1979; Smith et al. 1981a) are complex and require careful specification of intracanopy meteorological conditions, canopy structure, and biophysical characteristics which are not often available. Observational and analytical studies are consistent with the models in detailing the complexity of the problem (Miller 1971; Heilman et al. 1976; Bonn 1978; Byrne et al. 1979; Kimes 1979; Kimes et al. 1980; Millard et al. 1980; Soer 1980; Balick and Wilson 1981).

2. Ongoing work at the U. S. Army Engineer Waterways Experiment Station (WES) has as a major goal the ability to realistically predict thermal signatures of natural and cultural terrain features for any time-of-day and weather conditions. Work on models for complex vegetation canopies and planar unvegetated surfaces has pointed to the need to fill the gap between these extremes. A model for predicting the time-varying temperature for an unvegetated planar surface using material thermophysical properties and meteorological conditions has been developed under previous WES research (Balick et al. 1981). This model, the Terrain Surface Temperature Model (TSTM), is discussed in Part II of this report. Logically, the approach taken for the work reported herein,

the next step, was to develop a module, or submodel, for use in conjunction with the TSTM to account for the dominant effects of a simple layer of vegetation on thermal IR signatures of the terrain surface. Such a capability would be useful even if it only applied to the simplest of canopies in nonextreme environments. It would allow the TSTM to be extended to areas of lawn, pasture, and perhaps rangelands. The module developed in this context has been named VEGIE and is presented in this paper.

Objectives and Scope

3. The specific objective of the work presented herein was to develop the capability to predict the temperature of terrain scene elements which contain a simple layer of vegetation and to diagnose the effect of vegetation on remotely sensed temperatures of terrain elements. More complete and theoretical treatments of this problem are under way; VEGIE is designed for immediate application to thermal IR signature prediction and analytical studies. It was also required that the operational flexibility and simplicity of the planar surface model be maintained. Some of the more important of these characteristics are:

- a. Time dependence and fast response to environmental changes.
- b. Air temperature considered a state variable.
- c. Materials treated as horizontally and vertically homogeneous layers.
- d. Precipitation and condensation not considered.
- e. Spectral characteristics not considered at this stage of thermal signature prediction.
- f. Sensible and latent heat transfers included.
- g. Cloud type and amount considered.

Input information additional to that used in the TSTM is minimized by the use of empirical and quasi-empirical relationships for many parameters. Most of these relationships use coefficients which are taken from the literature and are not unique. Most of them could be replaced by measurements if measurements are available. Therefore, this report presents details of only the more basic concepts of the VEGIE module. The entire set of equations of the present configuration of VEGIE is, however, given in Appendix A along with a list of basic symbols.

4. The sensitivity of temperature estimates to the additional inputs required by VEGIE is examined. This is intended to examine the behavior of VEGIE and to help determine the limits of its validity. (A qualitative description of the sensitivity of TSTM is given along with a brief description of the model.) The model is then applied to a problem in terrain infrared signature prediction. In a scene element with less than total foliage cover there exists a mixture of materials (foliage, soil) with emissivities that may be different. The consequences of such mixtures are examined using VEGIE, with and without consideration of reflected sky radiation.

5. Results from VEGIE are compared to two days of data obtained in Germany in order to obtain a partial model validation. These results are also compared with output from a more complete vegetation model developed at Colorado State University (Smith et al. 1981a, 1981b). Finally, interesting results from applying VEGIE to forests are presented.

PART II: MODEL FRAMEWORK

Overview

6. The starting point for the development of the vegetation submodel was a temperature prediction scheme developed by Deardorff (1978). His procedures seem to be designed to provide an efficient way to account for boundary layer transfer of sensible and latent heat in atmospheric circulation models. Because Deardorff's procedure was developed for a different application and merged with different computational techniques, only portions of his work were found to be directly usable. These include the energy budget equations for the foliage and the ground surface, his treatment of foliage cover, and his techniques for scaling and interpolating parameters according to the degree of vegetative cover. Also, his equations for sensible and latent heat transfer from the ground were preserved. Major changes were made in the evaluation of terms of the foliage energy budget, the numerical routine for solving the energy budgets, and the overall computational sequence. Still, the key concepts are derived from Deardorff's work.

7. The flow of calculations between major components of the TSTM/VEGIE system is diagrammed in Figure 1. At block 1, the model is incremented one time step (or initialized or terminated) in accordance with procedures established for the TSTM. The flow then separates, depending on whether or not VEGIE is to be used. If not, a nonvegetated surface energy budget is evaluated as an upper boundary condition (block 3) for the solution of the equation for heat transfer through the terrain materials (block 6). The solution for the surface temperature comes from the evaluation of the surface energy budget equation, but solving the heat transfer equation is necessary to estimate the heat conduction term and to estimate the distribution of heat in the terrain materials. If VEGIE is to be used, the energy budget of block 3 is replaced by blocks 4 and 5. Blocks 4 and 5 constitute VEGIE. Block 4 is an evaluation of the energy budget for the foliage that includes a contribution from the ground surface. Evaluation of the ground energy budget is done in

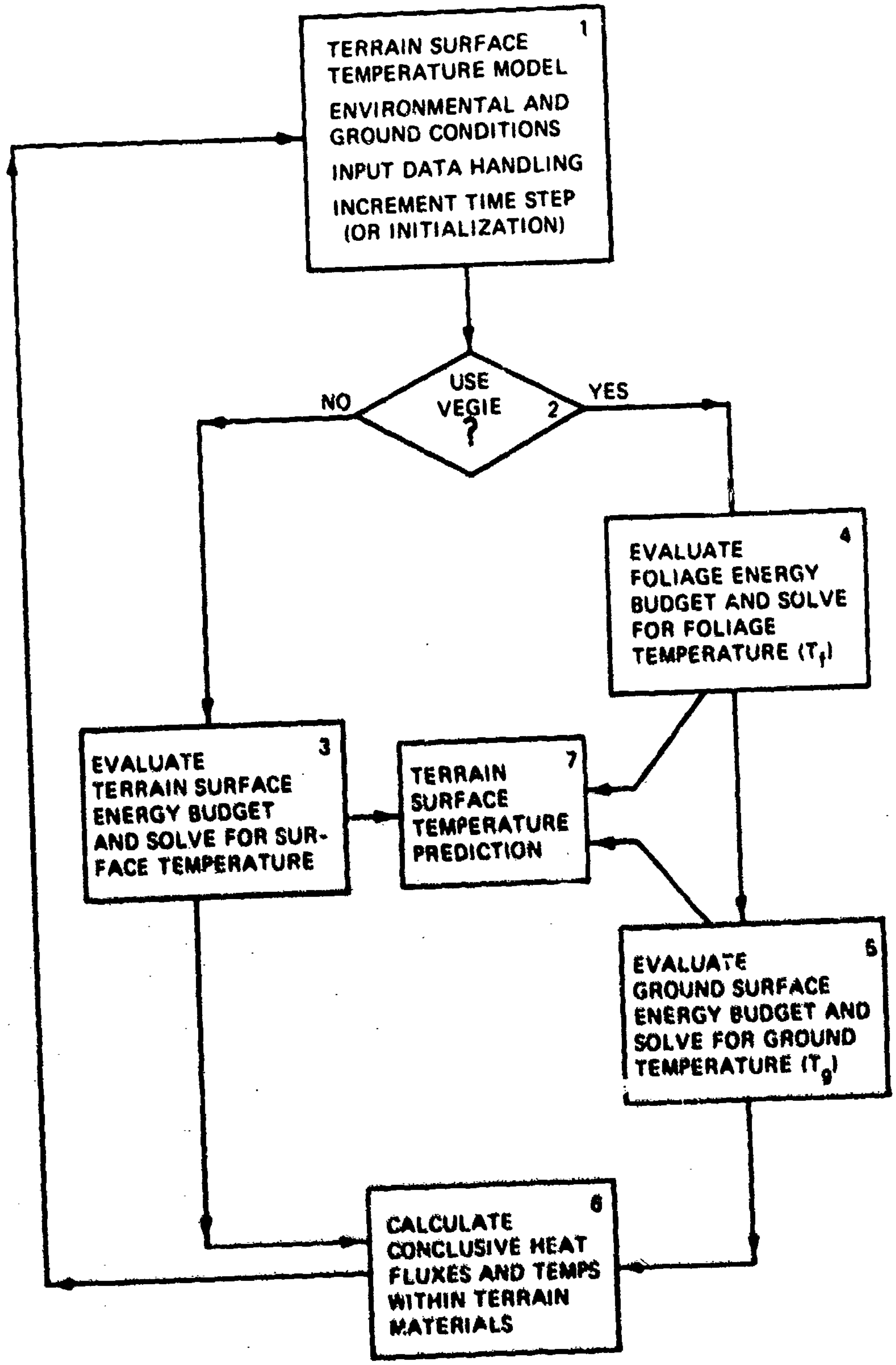


Figure 1. Sequence of calculation of the major components of the TSTM/VEGIE system

block 5, which includes a contribution from the foliage layer. (Solar and thermal IR from the sky incident on a plane above the vegetation are determined by procedures developed for the TSTM and are taken here as given.) Some details of the calculation of sky thermal IR radiation are given in Appendix A. Solutions of temperature for the foliage (from block 4) and the ground (block 5) are performed by a simple root-finding algorithm and are combined according to the proportion of foliage cover to yield an average or effective temperature of the vegetated surface. The ground energy budget is then used in the evaluation of heat flow in the terrain (block 6), and the program returns to block 1. The calculations of blocks 4 and 5 are the primary subjects of this report but a brief description of the TSTM is warranted.

TSTM

8. The TSTM solves the one-dimensional time-dependent heat flow equation for material systems of one to six horizontally and vertically homogeneous layers. The equation is written as

$$\frac{\partial T(z,t)}{\partial t} = \alpha(z)\,\frac{\partial^2 T(z,t)}{\partial z^2} \tag{1}$$

where T is temperature, z is distance into the material system, α is the thermal diffusivity, and t is time. The solution of this equation is done with straight explicit numerical techniques given an initial temperature profile and upper and lower boundary conditions which are energy budgets. The lower boundary condition is user-specified in a very simple fashion with three available options. The upper boundary is of greater interest; from it is derived the surface temperature estimate.

9. The heat budget of the top surface can be written as the sum of energy flux density components:

$$S + R_{s\downarrow} + R_{\uparrow} + H + E + G = 0 \tag{2}$$

where

S is the solar radiation absorbed at the surface

$R_{s\downarrow}$ is the downwelling thermal IR energy from the sky

$R_{\uparrow}$ is the thermal IR energy emitted by the surface

H is the sensible heat exchange

E is the evaporative heat exchange

G is the conductive transfer between the surface and the terrain material

This equation is rewritten as a nonlinear function, F , of the surface temperature such that the updated surface temperature is a zero of F . The Newton-Raphson algorithm is used to locate the value of T_s such that F is zero.

10. Each term of Equation 2 is evaluated separately. S is the global solar insolation multiplied by the absorptivity. Insolation is usually an input, but it is estimated by TSTM if it is not in the input file. Downwelling thermal IR from the sky is estimated with the Brunt equation with adjustments for cloud type and amount (Sellers 1965 or Oke 1978). $R_{\uparrow}$ is the graybody radiant emittance and H and E are evaluated with the "aerodynamic" approach to turbulent heat transfer (Oke 1978) with adjustments for stability. G is approximated by

$$G = K \frac{T_{s-1} - T_s}{\Delta z} \quad (3)$$

where K is the heat conductivity of the top layer, T_{s-1} is the temperature of the first grid point below the surface, and Δz is the distance between that point and the surface.

11. Inputs to TSTM include atmospheric constants and time-varying atmospheric and material properties. Atmospheric constants required are atmospheric pressure and instrument shelter height above the surface. The shelter height value represents the height above the ground that air temperature and wind speed are measured. Atmospheric time-varying data required include air temperature, relative humidity, cloud cover, wind speed, and total insolation. Solar insolation can also be computed as previously mentioned. Material properties are needed for the surface

and each of the layers. Surface properties required are thermal emissivity, optical absorptivity, and percent saturation of the surface. Each layer is defined by its thickness, thermal diffusivity, and heat conductivity.

12. Table 1 presents a qualitative assessment of model sensitivity to its input data. Figure 2 illustrates the response of the model to changes of time-varying atmospheric data; in this case the data are hourly and the only variable changes are cloud cover. TSTM is described in detail by Balick et al. (1981). A conceptually similar model has been developed by Kahle (1977).

13. Operationally, the only change needed to run VEGIE is to add a single line of data to the input file. If these data are present, the program bypasses the above top boundary energy calculations and proceeds as described below.

VEGIE

14. Description of the VEGIE module is done in four parts; the foliage energy budget (Figure 1, block 4), the ground energy budget (Figure 1, block 5), the root-finding algorithm used to solve each energy budget for temperature, and the combination of these temperatures to form an average temperature (Figure 1, block 7). The overall sequence of calculations has been discussed. The complete set of equations is given in Appendix A and their sources are referenced there.

Foliage energy budget

15. The equation for the foliage energy budget, F_f , is adopted directly from Deardorff (1978) and is

$$F_f = \sigma_f(\alpha_f S + \varepsilon_f R_{s\downarrow} + R_n) - H_f - E_f \qquad (4)$$

where σ_f is the fraction of foliage cover, α is the shortwave (solar) absorptivity, ε is graybody emissivity, the subscript f pertains to the foliage, and R_n is a combined "net" thermal IR term for interaction between the foliage, ground, and their loss to the sky. The equation for R_n is in Appendix A and is a function of the foliage and ground

Table 1

Relative Response of TSTM to Variation of Input Parameters

Very Sensitive	Moderately Sensitive	Very Insensitive
Air temperature	Relative humidity	Air pressure
Solar absorption	Shelter height	Cloud cover (high level clouds)
Thermal emissivity	Wind speed	Thermal diffusivity
Initial temperature profile	Cloud cover (middle level clouds)	Time step*
Saturation	Cloud type: (between high, middle and low level clouds)	Grid spacing*
Cloud cover (low level clouds)		24-hr repetitions
Top layer heat conductivity		Bottom boundary flux**

* Not sensitive, provided model is numerically stable.
** Not sensitive for thick systems with relatively low heat conductivity including most soils.

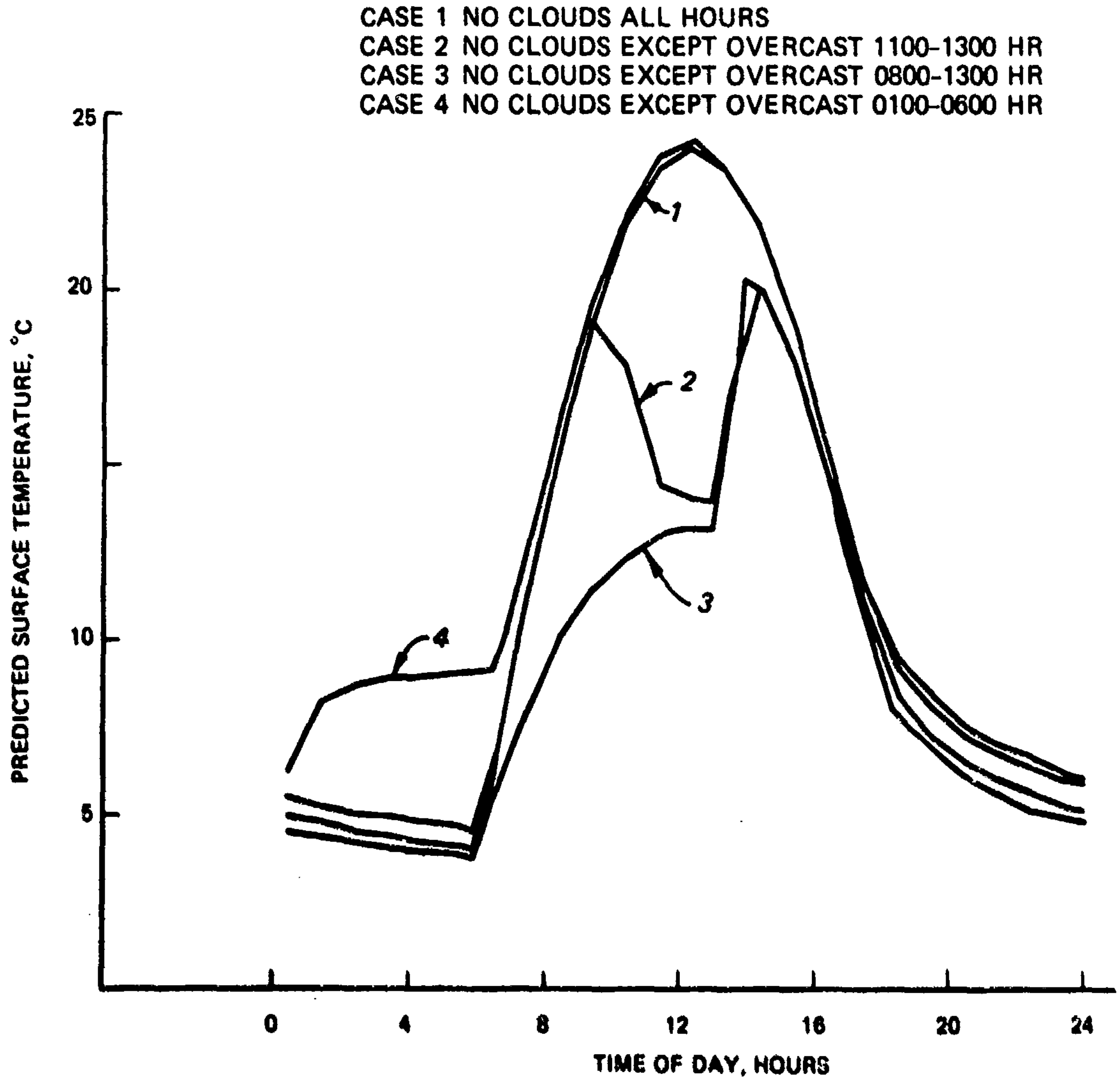


Figure 2. TSTM predictions of road surface temperature with time-varying cloud cover conditions (from Balick et al. 1981)

emissivities (ε_f , ε_g) and temperatures (T_f , T_g). The parameters σ_f , α_f , ε_f , ε_g are inputs to the model, S and $R_{s\downarrow}$ are inputs to and/or calculated by TSTM, T_g is the ground temperature estimate from the previous time step, and T_f is determined by the root-finding algorithm. Sensible heat transfers from the foliage are primarily functions of temperature, wind speed, and vapor pressure differences between the foliage or the air adjacent to it and the air at the instrument shelter height. Energy storage and conduction by the foliage are neglected.

16. Values of five foliage parameters are required for VEGIE. They are:

a. σ_f: foliage cover fraction, $0 < \sigma_f < 1$

b. χ: state of vegetation, $\chi > 0$

c. ε_f: graybody emissivity, $0 < \varepsilon_f < 1$

d. α_f: shortwave (solar) absorptivity of the layer, $0 < \alpha_f < 1$

e. Z_f: foliage height, $Z_f > 0$

17. Deardorff defines σ_f as an area average shielding factor associated with the degree to which foliage prevents shortwave radiation from reaching the ground. It is not the same as a visual cover because of single or multiple shortwave scattering by the leaves; σ_f is less than the degree visual cover to some extent. The range of σ_f is 0 to 1 and is assumed not to vary with sun zenith or azimuth angle. Deardorff provides typical values from Geiger (1965) as follows: 0.82 for meadow grass, 0.95 for 30-cm-high clover, 0.83 for 80-cm-high winter rye, 0.30 for summer barley 12-15-cm high, and from 0.4 to 0.98 for various stands of trees. The foliage cover parameter can be roughly related to leaf area index (LAI) for ground vegetation by:

$$\sigma_f \doteq LAI/7 \tag{5}$$

χ is used as a multiplier of the stomatal resistance function in VEGIE. An empirical relationship of stomatal resistance as a function of insolation for typical unstressed plants is used in VEGIE. Use of χ then allows rough adjustment for deviations from this curve by the user. Normally $\chi = 1.0$ is used, but other values can be chosen to adjust stomatal resistance for moisture stress, senescence, or other factors. The meaning of the other parameters is clear.

18. All of the radiant energy terms of the foliage energy budget, Equation 4, are weighted by σ_f, but the turbulent transfer terms are not weighted. These terms are evaluated for a unit of ground area. (One slight exception is in determining the value for the canopy resistance to water vapor diffusion for the E_f term; see Appendix A.) Equation 4 is solved for the value of T_f that makes $F_f = 0$.

Ground energy budget

19. Following Deardorff again, the energy budget for the ground is written as

$$F_g = (1 - \sigma_f)\alpha_g S + R_{g\downarrow} - R_{g\uparrow} - H_g - E_g - G \qquad (6)$$

The adjustment of insolation for foliage cover is clear and no adjustment is appropriate for the conduction term, G. Otherwise, adjustments for foliage density are made in evaluating the terms. Terms for incoming and outgoing thermal IR flux density, $R_{g\downarrow}$ and $R_{g\uparrow}$, are each functions of T_g, T_f, ε_g, ε_f, and $R_{s\downarrow}$ and equations include reflection. Evaluation of the turbulent energy transfer terms for the foliage energy budget is done per unit ground area and with the assumption that the exchange takes place directly between the foliage and the air above it. Turbulent transfer at the ground is still per unit area but is buffered by the layer of vegetation and, thus, is a function of σ_f. Additionally, the transfer occurs between the ground and the air within the foliage layer which is an arbitrary mixture of conditions at the ground, foliage, and air at shelter height. The evaluation of these terms follows Deardorff very closely. Conduction is estimated with Equation 3 as in the base ground energy budget. The root-finding algorithm is used to find the value of T_g that makes $F_g = 0$.

Root-finding algorithm

20. The objective of the root-finding algorithm is to find the

temperature, T_f or T_g , for which the sum of the energy budget components is zero (or within a specified range from zero). Solved for temperature, the energy budgets are fourth-order equations but experience has shown that there is only one real and reasonable root given realistic conditions. Therefore, a very simple and efficient algorithm, similar to those in software packages used for many microcomputers, was adapted for VEGIE and is called the regula falsi technique (Scheid 1969).

21. Figure 3 schematically illustrates the steps in the algorithm. An initial guess of temperature, T , is made which is unrealistically low (say 200°K) such as point A, in Figure 3a. The energy budget, $F = f(T)$, (Equation 6 or 8) is evaluated there and its sign is determined. F is reevaluated at progressively higher temperatures at regular steps (say 5°K) until the sign of F changes. Points A and B in Figure 3b are determined. The intercept of a straight line between points f(A) and f(B) is found; point C in Figure 3c. Then $f(A)$ becomes $f(C)$, a new line between $f(A)$ and $f(B)$ is determined, a new intercept is found (Figure 3d) and so on until F is less than some assigned value ($F \leq 0.001$ for VEGIE). This algorithm is simple, straightforward, and easily adaptable to microcomputers for functions that behave like F .

Effective temperature

22. The simplest procedure for combining ground and vegetation temperature would be a simple average weighted by the foliage cover:

$$\bar{T} = \sigma_f T_f + (1 - \sigma_f) T_g \tag{7}$$

However, when temperatures are observed radiometrically, it is more appropriate to mix the radiant exitance from the two materials and solve for temperature as follows:

$$\bar{T} = \left[\sigma_f \varepsilon_f T_f^4 + (1 - \sigma_f) \varepsilon_g T_g^4\right]^{0.25} \tag{8}$$

Except as otherwise stated, all model results presented in following sections are effective temperatures as defined in Equation 8. The effective temperature value is the primary product of the TSTM/VEGIE system.

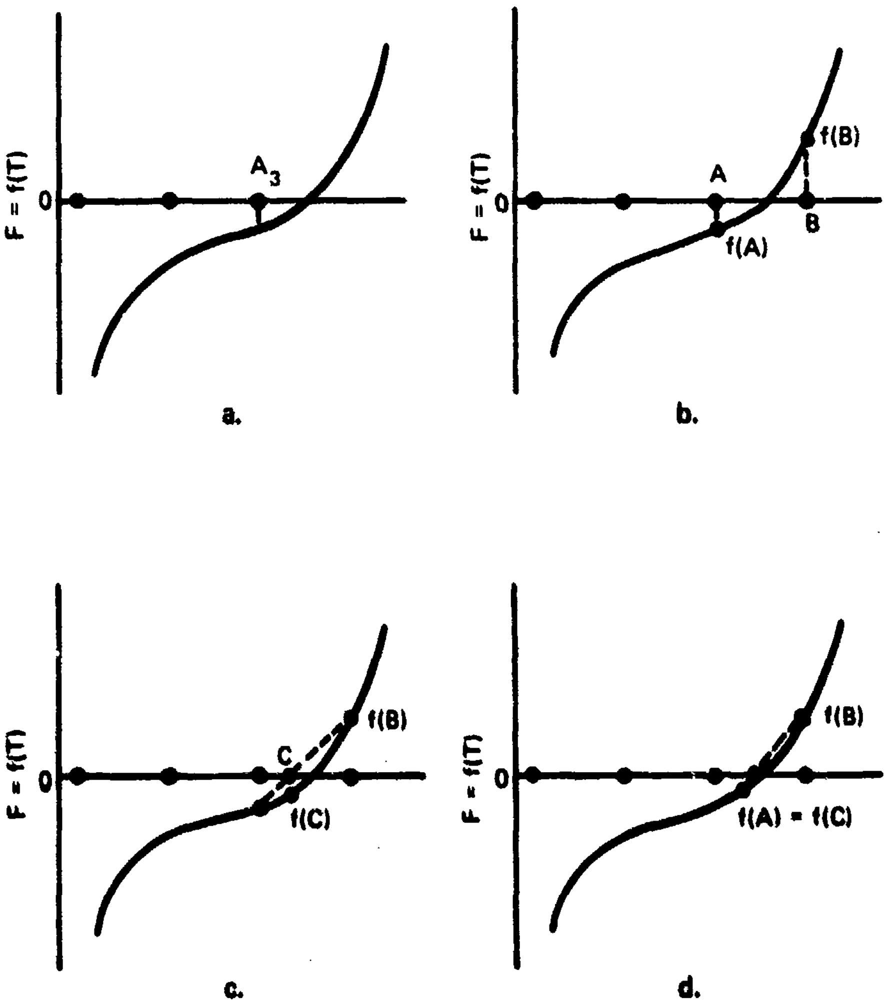


Figure 3. Schematic representation of the root-finding algorithm (regula falsi)

PART III: SENSITIVITY AND VERIFICATION

23. This section presents a brief analysis of the sensitivity of temperature estimates to the input vegetation parameters required by VEGIE. Model estimates are then compared to two days of real data and estimates from a more complex model for the same two days. Model estimates for two tree canopies are presented as cases where the concepts of VEGIE are not valid, but the counterexamples are informative. Lastly, VEGIE is applied to examining the effects of emissivity mixtures within scene elements on thermal IR signature prediction and analysis.

Sensitivity

24. The sensitivity of VEGIE to its input variables was examined by allowing each of the variables to vary over a large range, while holding other variables the same for one arbitrary but real diurnal cycle of environmental conditions. The change of model estimates as a function of parameter value is then isolated for that case. Figure 4 shows the sensitivity of model estimates to changes of σ_f . The curves are the highest and lowest temperature for a complete diurnal cycle at different foliage covers. In Figure 4a, minimum effective temperature estimates are almost unchanged across the range of σ_f . Maximum effective temperatures are strongly affected by changes of σ_f at low values but when $\sigma_f > 0.7$ there is almost no effect. These curves are a combination of changes in energy transfers and the mixture of ground and foliage used in averaging to obtain effective temperatures. Similar curves, but for ground and foliage temperatures separately, are given in Figure 4b. This removes the averaging ambiguity and clearly illustrates that the ground temperature estimates are far more sensitive to changes of σ_f than foliage temperature estimates. This implies that foliage temperatures do not change much with the density of foliage cover. Expectedly, maximum ground temperature estimates are more affected than minimum temperatures.

25. VEGIE was found to be highly insensitive to changes of the other four foliage parameters. For one parameter at a time, each of the

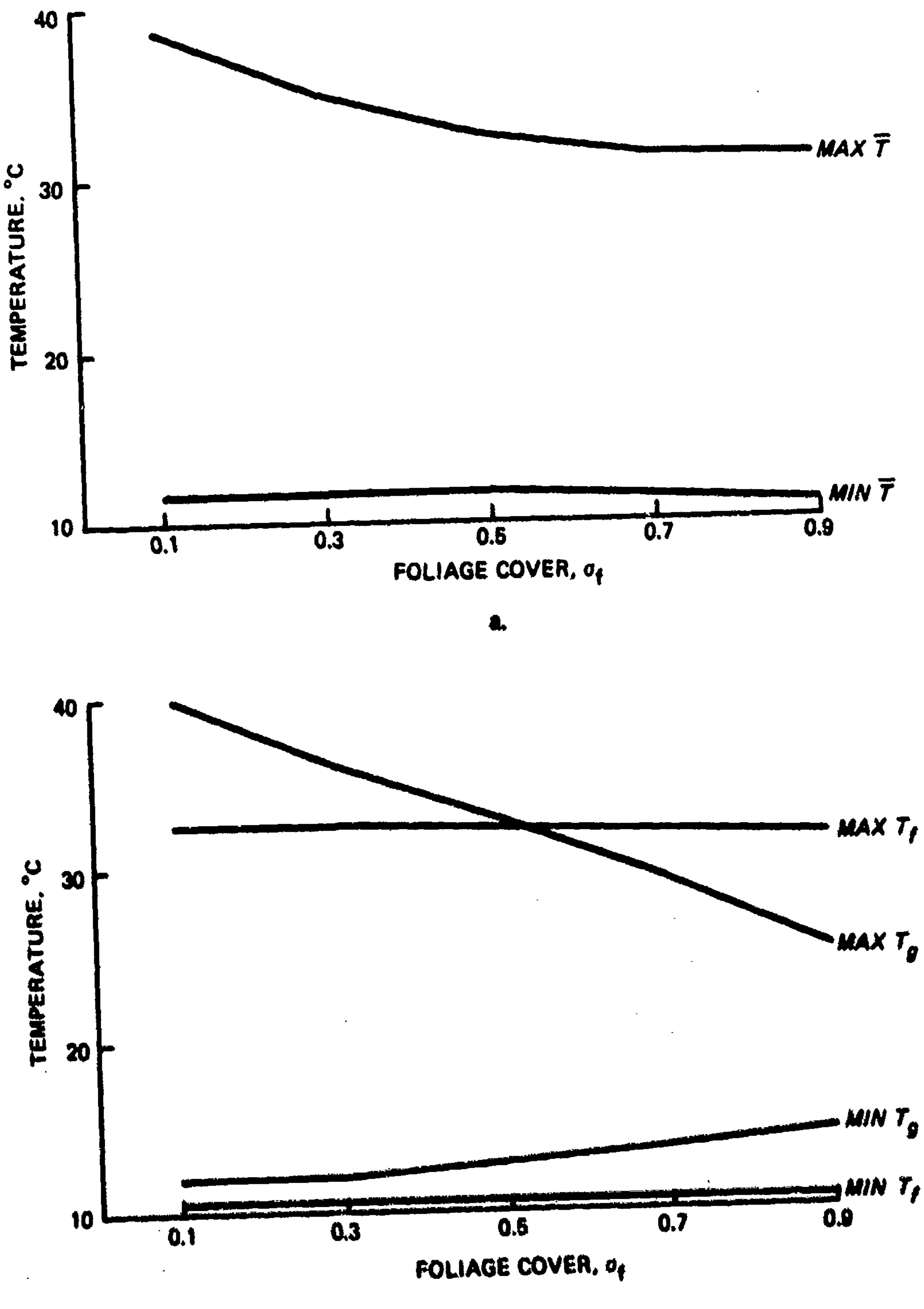


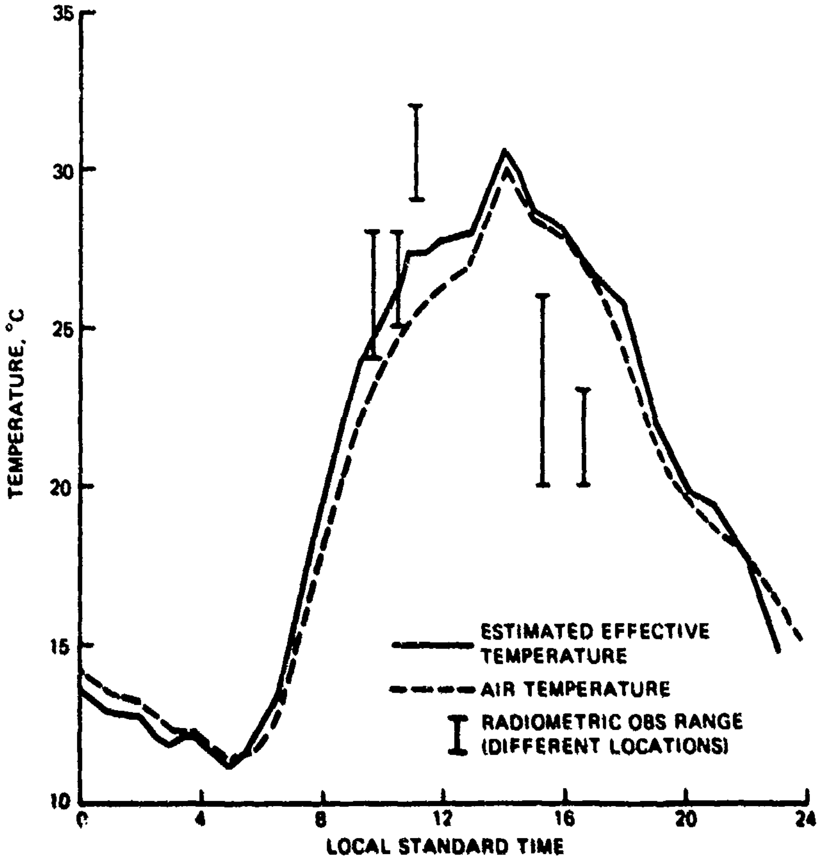
Figure 4. Sensitivity of temperature estimates to variation of foliage cover when conditions are those of Zweibruecken Air Force Base, West Germany, on 1 September 1979

four inputs were varied over an unrealistically large range of values, and neither maximum nor minimum temperature estimates changed by more than 1°C. A close look at the energy budget components showed that there is an underplay or feedback between them. That is, when χ was raised to 1000, E_f was reduced to near zero. However, other terms, most notably H_f, changed to compensate for the reduction of latent heat loss. Such feedbacks do exist in nature, and in moderate and unstressed conditions, temperatures are closely coupled to air temperature. The results with VEGIE are consistent with this situation. Only extensive comparison with careful measurements can indicate the extent to which these model responses represent real conditions.

Verification

26. Figure 5 contains the model estimates of terrain temperature and air temperature over two diurnal cycles; 1 September 1979 in Figure 5a and 10 October 1979 in Figure 5b. Ranges of radiometric temperatures are shown as vertical bars at the time of observation. The data were obtained at Zweibruecken Air Force Base, West Germany, during the course of a North Atlantic Treaty Organization (NATO) field experiment. On 1 September 1979 the weather was warm with the sky changing from clear to 0.4 or 0.5 cover of cirrus clouds after 0900 local standard time (LST). On 11 October 1979 the weather was cooler with the sky changing from clear to 0.9 or 1.0 cover of stratocumulus clouds after about 0400 LST. TSTM estimates of solar insolation are used in lieu of observations for both days. Vegetation is rough, unstressed grass about 10 cm high.

27. Examination of Figure 5 reveals that model estimates follow air temperatures closely but that they do deviate in a manner that would be expected given time of day and cloud cover. More importantly, these deviations are generally of the same signs and magnitudes as measurements indicate are real. The measurements on 1 September 1979 were made by a variety of observers using different instruments at different sites. Thus, observations that deviate markedly from air temperature might be



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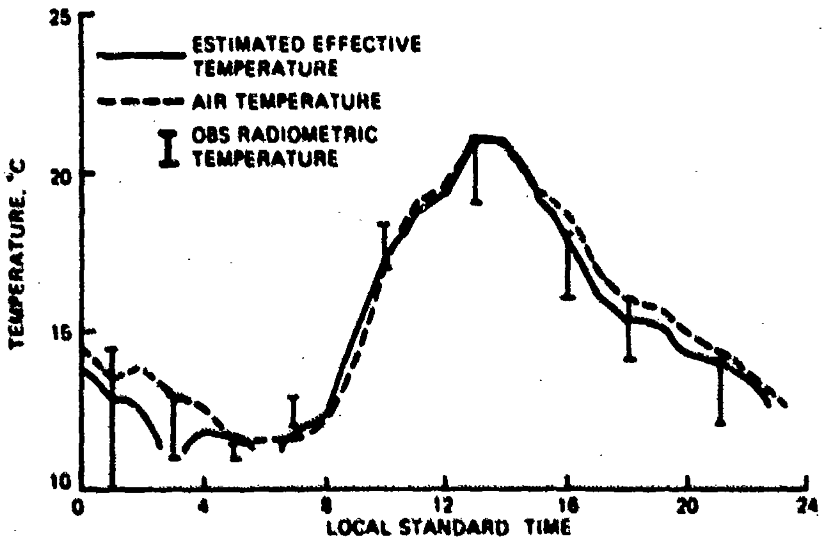


b. ZWEIBRUCKEN AFB, GE, 11 OCT 79

Figure 5. Model estimates and radiometric observations of terrain temperatures and air temperatures for two days at Zweibruecken Air Force Base, West Germany, $\sigma_f = 0.85$, $\chi = 1.0$, $\varepsilon_f = 0.98$, $\alpha_f = 0.75$, $Z_f = 10$ cm

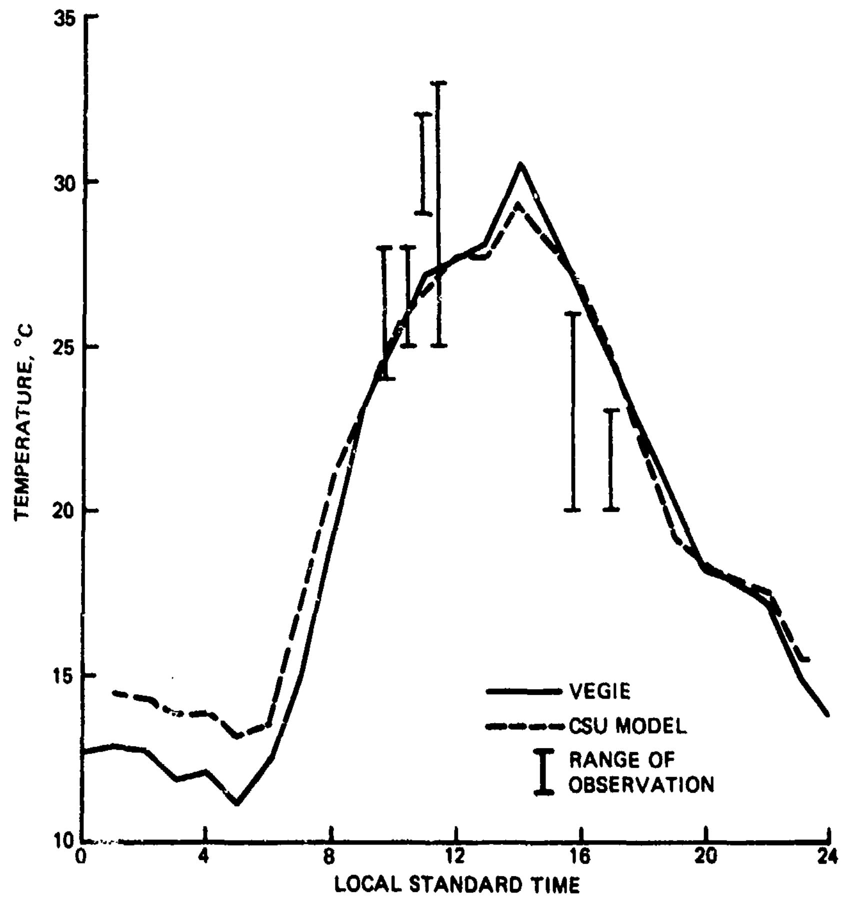
invalid. If so, the performance of VEGIE must be considered quite good for the very moderate conditions on these test days.

28. What accuracy is lost in using a simple model instead of a complex model on the grass canopies for these days? Are the simplifications of more elaborate theoretical procedures valid? A means to answer these questions more completely is the Thermal Vegetation Canopy Model developed at Colorado State University (CSU) (Smith et al. 1981a, b). This model was run on the same canopy and for the same two days as in Figure 5. Additionally, the same TSTM insolation estimates and VEGIE ground surface temperature estimates were used in the CSU model calculations. (Ground temperatures are a required input to the CSU model.) This last feature implies that the differences in results are due to differences in foliage temperature estimates and procedures used to derive an effective temperature.

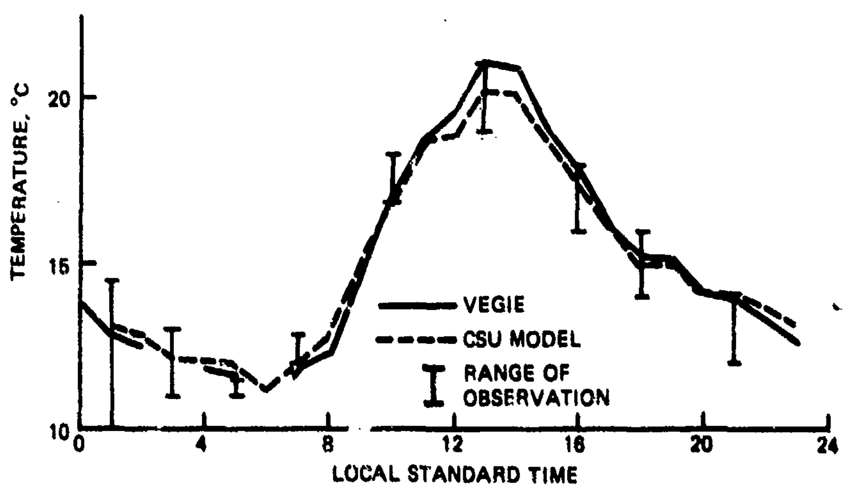
29. Estimates from the two models are very similar as can be seen in Figure 6. Only occasionally are the results from the two models more than 1°C different, mostly for the morning of 1 September 1979. VEGIE estimates of the maximum temperature on both days are about 1°C warmer than the CSU model but the difference is short-lived. The source of different results of the two models has not been specifically determined. In any case, not much predictive accuracy is lost in using VEGIE on the simple layer of vegetation; much time and effort can be saved.

30. During the summer of 1979, two collaborative experiments were done to obtain data to derive and validate canopy thermal IR signature models in forest situations (Smith et al. 1981a). Two complete diurnal cycles of data were obtained in a Douglas-fir canopy (28 m high, Cedar River, near Issaquah, Wash.) and two more in a mixed deciduous canopy (21.5 m high, Walker Branch near Oak Ridge, Tenn.). The temptation to run VEGIE on these data sets was not resisted. Forest canopies are, however, outside of the range of conditions intended for the use of VEGIE.

31. Figure 7 contains the results from the Walker Branch, Tenn., deciduous canopy on 18 and 19 August 1979. Unlike the estimates for Germany, ground temperatures for the CSU model were measured with a handheld radiometer. The two models agreed very well at night, but VEGIE



a. ZWEIBRUCKEN AFB, GE, 1 SEP 79



ZWEIBRUCKEN AFB, GE, 11 OCT 79

Figure 6. Comparison of VEGIE and Colorado State University model estimates and observations (VEGIE estimates and observations are the same as in Figure 5)

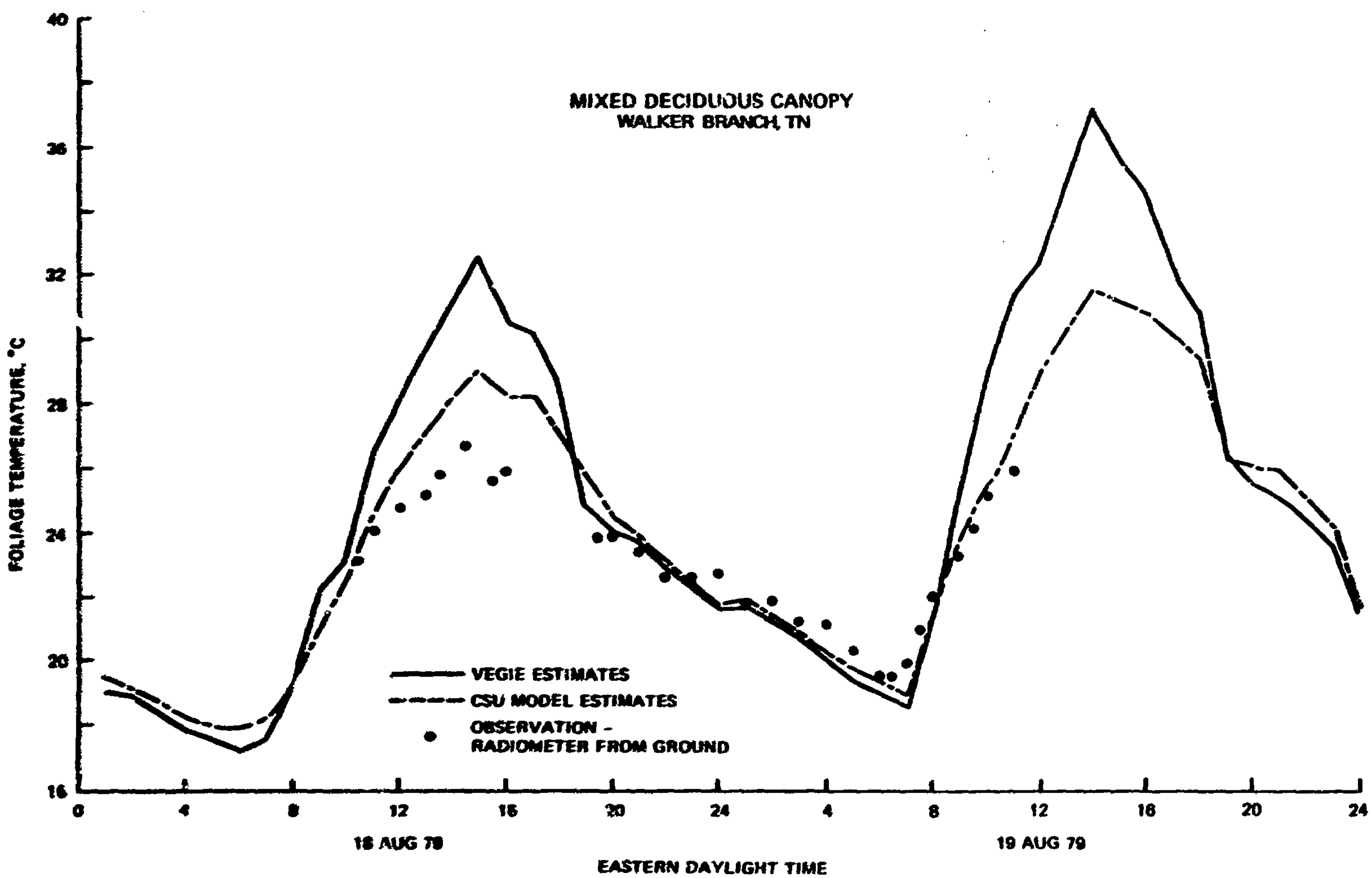


Figure 7. Comparison of models and observations when applied to a 21.5-m-tall mixed deciduous forest canopy at Walker Branch, Tenn., on 18 and 19 August 1979

seriously overpredicts temperature during the day. Similar results were obtained for the Douglas-fir canopy at Cedar River, Wash., on 4 and 5 August 1979. These results are shown in Figure 8. VEGIE seems to track well with the radiometric measurements made from the ground, but this is probably not significant. Thermocouple measurements are superior in this case and should be used as the standard for comparison. Also notable is a tendency for VEGIE to predict slightly lower temperatures than the CSU model.

32. Close examination of the daytime overestimation of forest canopy temperatures indicates that the magnitude of the error is more closely related to insolation than any other environmental variable. The equations in VEGIE describe the solar irradiation on the foliage as occurring on a porous but single flat surface. In nature and in the CSU model (and many other models as well), the solar energy is vertically distributed throughout the canopy. That simplification for VEGIE may, at least in part, explain VEGIE's tendency to overestimate temperatures during the day. The lack of a vertically distributed canopy in VEGIE may also be responsible for its nocturnal underestimates. It would be fortunate if these speculations were accurate because the problem would be greatly reduced for grassy canopies; heights are on the order of 20 cm instead of 20 m. There is only a hint of such behavior in the grass canopy simulations given in Figure 5.

Application: Mixed Emissivities

33. Transformation of temperature estimates to thermal IR signatures requires specification of emissivity. When a simple foliage layer partially covers a soil surface, a sensor receives energy emitted from both in proportion to the amount of cover, their emissivities, and their temperatures. Additionally, the sensor receives thermal IR energy reflected by the surface materials from the sky and surroundings. Radiation from the sky and this reflection varies mainly with atmospheric temperature and water vapor and clouds and is then time-dependent. Varying mixtures of emissivity also affect energy flumes and transformations

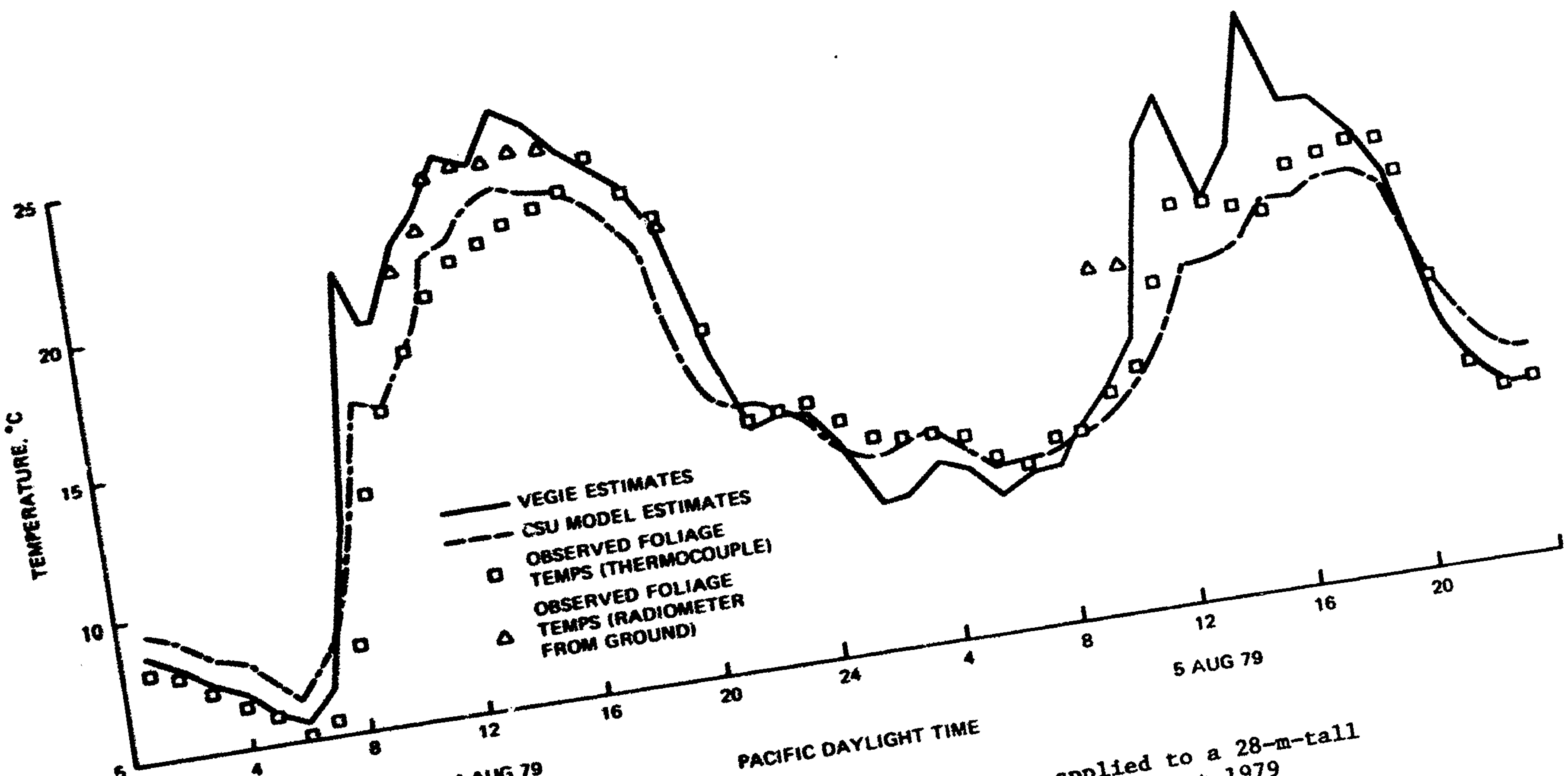


Figure 8. Comparison of models and observations when applied to a 28-m-tall Douglas-fir canopy at Cedar River, Wash., on 4 and 5 August 1979

to some extent. Clearly, the effects of emissivity mixtures within a scene element can be a critical issue on signature prediction and analysis. They are examined in two ways in this section. First, a single arbitrary case is presented where only the foliage cover and ground emissivity are varied. Secondly, VEGIE is used to examine the more complex case where environmental conditions and energy budget changes are considered.

34. The thermal IR energy emitted per unit time and area, W_t, for a surface composed of foliage and ground is

$$W_t = \sigma_f \varepsilon_f \sigma T_f^4 + (1 - \sigma_f)\varepsilon_g \sigma T_g^4 \tag{9}$$

For a graybody near thermal equilibrium, thermal IR reflectivity is $(1 - \varepsilon)$. Thus, a sensor pointed down at a grass/ground surface would receive emitted and reflected radiation from the surface. Ignoring multiple reflection and atmospheric, spectral, and directional effects, this quantity is

$$\begin{aligned} W_t = {} & \sigma_f \varepsilon_f \sigma T_f^4 + (1 - \delta_f)\varepsilon_g \sigma T_g^4 \\ & + (1 - \sigma_f)(1 - \varepsilon_g)\varepsilon_a \sigma T_a^4 + \sigma_f (1 - \varepsilon_f)\varepsilon_a \sigma T_a^4 \end{aligned} \tag{10}$$

(For a more complete treatment see Lorenz (1966)) where the subscript a indicates values for the atmosphere. W_t from Equations 9 and 10 can be converted to average effective temperature with

$$\bar{T} = \left(\frac{W_t}{\sigma}\right)^{0.25} \tag{11}$$

Foliage emissivities are generally greater than 0.95 and usually about 0.98 (Gates 1980); whereas, mineral soil emissivities can be considerably lower (Taylor 1979; Holmes, Nuesch, and Vincent 1980; Buettner and Kern 1966) and, in the field, are less well known. Figure 9a shows the variation of $\bar{T}$ with changes of σ_f and ε_g for an arbitrary case, with and without consideration of reflection. Figure 9b shows the error from

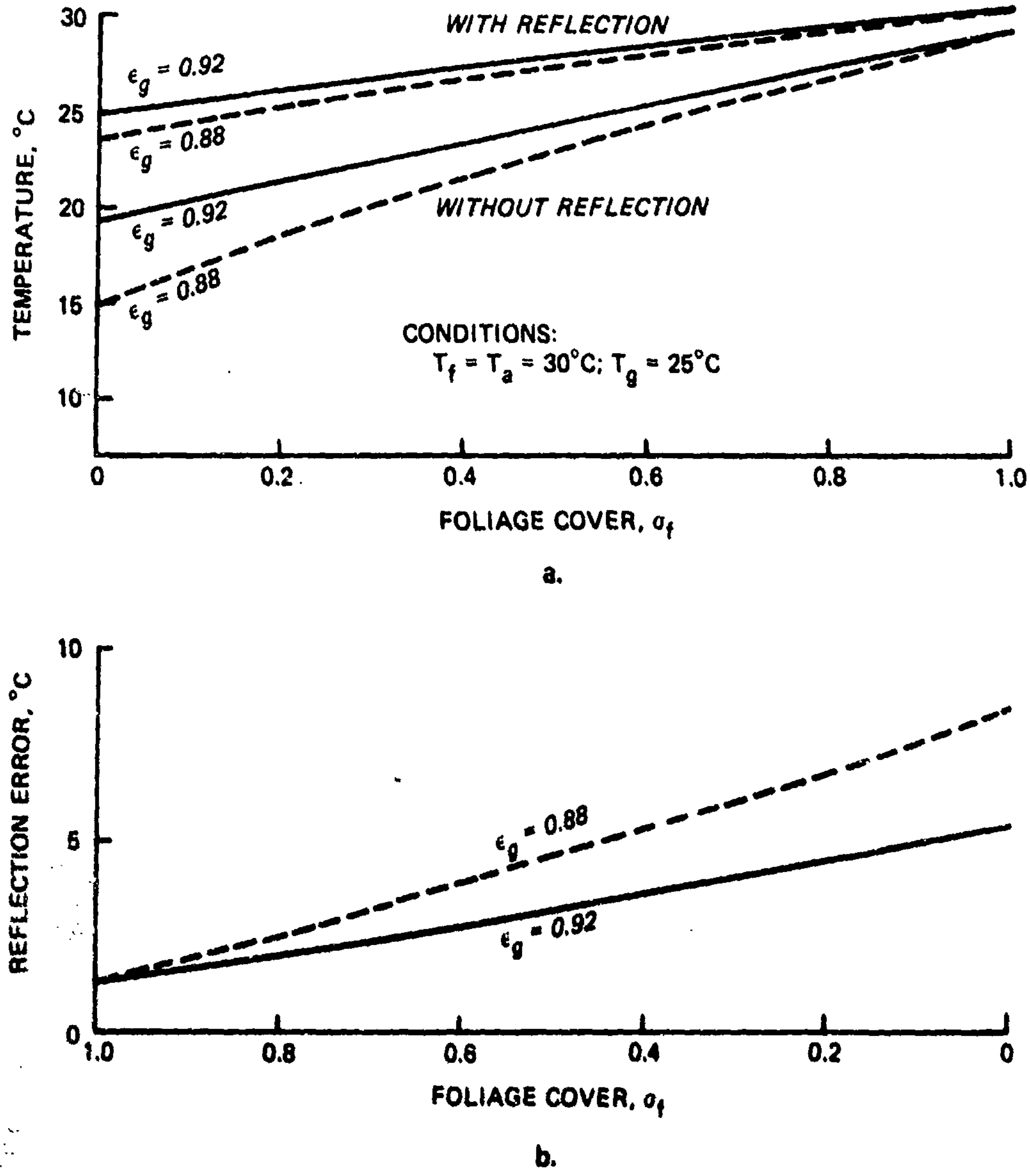


Figure 9. Comparison of effective temperatures as a function of foliage cover with different soil emissivities and with and without considerations for reflected sky thermal IR irradiance

neglecting reflection as a function of σ_f for two values of ε_g. When reflection is not considered, an uncertainty of 0.04 in ε_g results in a 4°C error in $\bar{T}$ at $\sigma_f = 0$ and about 1.5°C at $\sigma_f = 0.5$ and is small above $\sigma_f = 0.8$. Errors of emissivity affect the reflection terms in the opposite direction which greatly reduces the net effect. Errors caused by ignoring reflection in this case are greater than 5°C for $\varepsilon_g < 0.92$ at $\sigma_f = 0$, greater than 3°C at $\sigma_f = 0.5$, and always greater than 1°C. Treating bare ground as a blackbody ($\varepsilon_g = 1$ and no reflection) results in an error of 8.5°C. These figures are for a reasonable but arbitrary case.

35. The use of VEGIE easily permits a similar analysis but for the course of an entire day and for specific environmental and terrain situations. Since reflection is a function of atmospheric temperature and humidity through T_a and ε_a, it is subject to changes in time as well as surface composition. The use of VEGIE to diagnose these effects can give a somewhat different picture than that in Figure 9 and can be very important in efforts to use and predict thermal IR signatures.

36. The curves plotted in Figure 10 are model estimates of maximum and minimum temperatures as a function of σ_f for a real case. The case is the same as in Figure 5a, 1 September 1979 at Zweibruecken Air Force Base, West Germany. Temperatures are defined by Equations 9, 10, and 11. The magnitude of the reflection effects is similar to those in Figure 9a but is larger for the maximum temperatures than the minimum. The predicted range of $\bar{T}$ as a function of σ_f varies from about 1°C for minimum temperatures to about 9°C for maximum temperatures; both extremes occur with reflection considered. Importantly, the shapes of the curves in Figures 9a and 10 are radically different. According to VEGIE, the minimum diurnal range is found at intermediate values of foliage cover--at $\sigma_f = 0.6$ without reflection and at $\sigma_f = 0.8$ with reflection. These kinds and magnitudes of effects, due to reflection and uncertainty of effective emissivity, are significant for the prediction, interpretation, and analysis of thermal IR measurements.

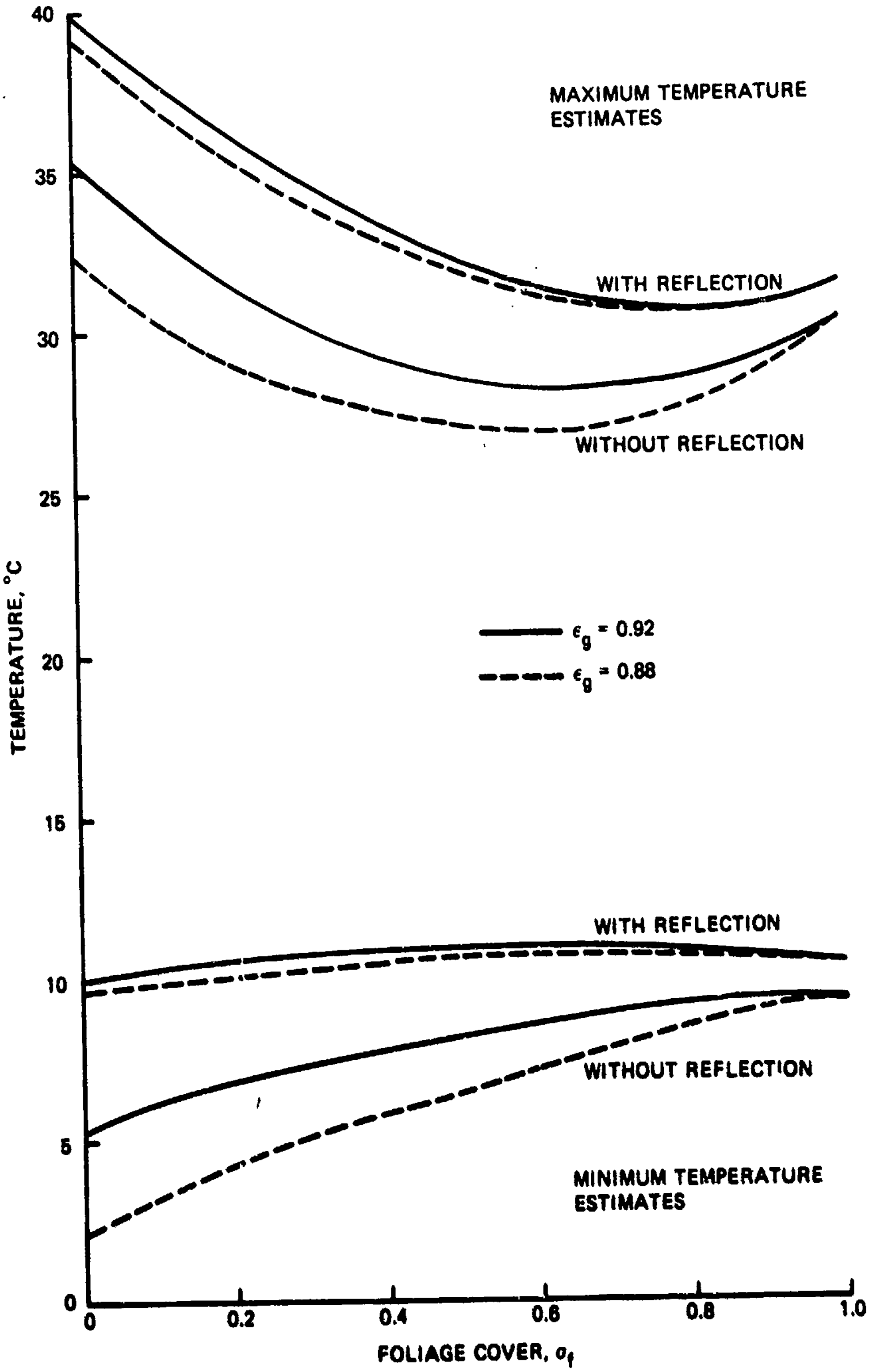


Figure 10. VEGIE estimates of maximum and minimum terrain temperature for conditions of varying foliage cover (σ_f) and ground emissivity (ε_g) with and without reflection of sky thermal IR irradiance

PART IV: CONCLUSIONS AND RECOMMENDATIONS

37. The highly simplified treatment of the energy budgets of foliage and ground in VEGIE seems valid for the simple cases it is designed to handle. This conclusion is indicated by the results obtained for the Zweibruecken Air Force Base grass canopy, as discussed in paragraphs 26 and 27. However, the module is not designed to be valid for all canopies. Results from the application of VEGIE to forest canopies, presented in paragraphs 30 and 31, show that VEGIE does not perform well in these complex canopies. VEGIE estimates of temperature are sensitive to changes of foliage cover but not very sensitive to the other canopy descriptors (paragraphs 24 and 25). This implies that VEGIE may not perform well under environmental conditions where turbulent heat transfers and plant responses are inadequately described.

38. It is recommended that additional sets of validation or test data be obtained in order to better define the canopy and environmental conditions where VEGIE is valid. Additional but limited development of simple models seems warranted. It is recommended that a simple treatment of canopy radiation penetration be developed for VEGIE to account for the vertical distribution of foliage. The long-term development of simple models, however, is limited for several reasons. These include the necessity to adequately specify intracanopy environmental conditions, plant physiological parameters, and the structure of the canopy itself. More importantly, there is a lack of fundamental understanding of turbulent transfers of energy in plant canopies; better predictive capability awaits a better theoretical base. Long-range advances in operational prediction of thermal IR signature of vegetation will likely best be made through the simplification and adaptation of complex models and theoretical developments.

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APPENDIX A: ENERGY BUDGETS AND TERM DEFINITIONS

Foliage

$$F_f = \sigma_f(\alpha_f S + \varepsilon_f R_{s\downarrow} + R_n) - H_f - E_f$$

$\alpha_f S$: α_f is input; S is input or estimated in TSTM

$\varepsilon_f R_{s\downarrow}$: ε_f is input; $R_{s\downarrow}$ from TSTM (Balick et al. 1981*)

$R_n = R_1 - R_2$ where

$$R_1 = (\varepsilon_f \varepsilon_g / \varepsilon_1)\sigma T_g^4$$

$$R_2 = [(\varepsilon_1 + \varepsilon_g)/\varepsilon_1]\varepsilon_f \sigma T_f^4$$

where $\varepsilon_1 = \varepsilon_f + \varepsilon_g - \varepsilon_f \varepsilon_g$ (from Deardorff 1978)

$$H_f = -\rho_{af} C_p k^2 Z^2 \frac{\Delta U}{\Delta Z} \frac{\Delta \theta}{\Delta Z}$$ (Balick et al. 1981; Oke 1978)

$$E_f = (\rho_{af} C_p / 0.66)[e_s(T_f) - e(T_a)]/(r_a + r_c)$$ (Gates 1980; Lee 1978).

Ground

$$F_g = (1 - \sigma_f)\alpha_g S + R_{g\downarrow} - R_{g\uparrow} - H_g - E_g - G$$

$(1 - \sigma_f)\alpha_g S$: σ_f and α_g are inputs; S as above.

$$R_{g\downarrow} = (1 - \sigma_f)R_{s\downarrow} + \sigma_f[\varepsilon_g \sigma T_g^4 + (1 - \varepsilon_g)\varepsilon_f \sigma T_f^4]/\varepsilon_1$$ (Deardorff 1978)

$$R_{g\uparrow} = (1 - \sigma_f)[\varepsilon_g \sigma T^4 + (1 - \varepsilon_g)R_{s\downarrow}] + \sigma_f[\varepsilon_g \sigma T_g^4 + (1 - \varepsilon_g)\varepsilon_f T_f^4]\varepsilon_1$$
(Deardorff 1978)

$$H_g = \rho_{ag} C_p C_{Hg} U_{af}(T_g - T_{af})$$ (Deardorff 1978)

$$E_g = \rho_{ag} C_{Hg} U_{af} L(q_g - q_{af})$$ (Deardorff 1978)

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* References cited in this Appendix are more fully identified in the References section at the end of the main text.

$G = -K(T_x - T_g)/Z_x$ T_x is the temperature at the first grid point below the surface, distance Z_x, in TSTM heat transfer algorithm.

Additional Definitions and Relationships Needed to Evaluate Heat Budget Terms

$R_{s\downarrow} = \sigma T_a^4(0.61 + 0.050\sqrt{e_a})(1 + K_1 n^2)$
where n is the decimal portion of cloud cover and K_1 is a coefficient dependent on cloud type (Balick et al. 1981; Oke 1978; Sellers 1965).

$\Delta Z = Z$; Z is the height above the ground where the temperature and wind speed are measured.

$\Delta U = U_a - U_{af}$; U_{af} is defined below.

$\Delta\theta = \theta(T_a) - \theta(T_f) = \theta(T_a - T_f)$ where

$\theta(T) = T(1000/P)^{0.286}$; definition of potential temperature.

$\rho_{af} = 0.348P/[(T_a + T_f)/2]$; from the ideal gas law assuming dry air (Lee 1978).

$e_s(T_f) = 6.108\exp[17.269(T_f - 273.16)/(T_f - 35.8)]$ Teten's equation for saturation vapor pressure as given by Murray (1967).

$e(T_a) = e_s(T_a)/RH$ where RH is the relative humidity.

$r_a = U_a/U_*^2$ U_* is the friction velocity defined by

$U_* = kU_a/\{\ln[(Z_a - Z_d)/Z_o]\Gamma\}$ (Oke 1978)

where $Z_d = 0.701 * Z_f^{0.979}$ is the zero displacement height

and

$Z_o = 0.131 * Z_f^{0.997}$ is the roughness length. Z_f is the foliage height (Rosenberg 1974).

$\Gamma = C_1(1 - C_2 Ri)^{C_3}$ is a correction factor for stability (Oke 1978).

$C_1 = 1.0 \quad C_2 = 5.0 \quad C_3 = 2.0$ if $Ri > 0$ (Oke 1978)

$C_1 = 1.175 \quad C_2 = 15.0 \quad C_3 = 0.75$ if $Ri \le 0$ (Lamb 1974)

$Ri = \{g/[\theta(T_a) + \theta(T_f)]/2\}[(\Delta\theta/\Delta Z)/(\Delta U/\Delta Z)^2]$ where g is the acceleration due to gravity. If $Ri \ge 0.2$, Ri is set equal to 0.199.

$r_a = \{\ln[(Z - Z_d)/Z_o]\Gamma\}^2/(k^2 U_a)$.

$r_c = \chi r_s/LAI$ and is the canopy resistance to water vapor diffusion where

$r_s = (0.05 + 0.0021S)^{-1}$ (Gates 1980) and is the stomatal resistance

$LAI \doteq 7\sigma_f$ (Deardorff 1978) and is the leaf area index.

$\rho_{ag} = 0.348P/T_{af}$ as for ρ_{af}

$T_{af} = (1 - \sigma_f)T_a + \sigma(0.3T_a + 0.6T_f + 0.1T_g)$ a mixture equation (Deardorff 1978).

$C_{Hg} = (1 - \sigma_f)C_{H_o} + \sigma_f C_{H_h}$; heat transfer coefficient equation, interpolated between ground with no cover (C_{H_o}) and complete cover (C_{H_h})(Deardorff 1978)

$C_{H_o} = k^2/\ln(Z_a/Z_u)^2$

$C_{H_h} = k^2/\{\ln[(Z_a - Z_d)/Z_o]\}^2$.

$U_{af} = 0.83\sigma_f U_a C_{H_h}^{1/2} + (1 - \sigma_f)U_a$; mixture (Deardorff 1978).

$q_f = r'' q_s(T_f) + (1 - r'')q_{af}$ (Deardorff 1978)

$r'' = r_a/(r_s + r_a)$

$$qs(T_f) = 0.622/[P/e_s(T_f) - 0.378] \ .$$

$$q(T_a) = 0.622/[P/e(T_a) - 0.378] \ .$$

$$q_{af} = (1 - \sigma_f)q(T_a) + \sigma_f[0.3q(T_a) + 0.6q_f + 0.1q_g]$$

$$q_g = Wq_s(Tg) + (1 - W)q_{af} \ .$$

Basic Symbols

Energy budget component - flux per unit area

S Solar irradiance at the top of the canopy

R Thermal infrared irradiance

H Sensible heat exchange with the atmosphere

E Latent heat loss to the atmosphere

G Conduction of heat in the top soil layer

Physical properties

T Temperature

P Pressure

ρ Air density

U Wind speed

q Specific humidity

Coefficients

σ_f Effective foliage cover, decimal fraction

ε Graybody thermal infrared emissivity

α Solar absorptivity (1 - reflectivity)

C Heat transfer coefficient

W Relative saturation of the ground near the surface with respect to field capacity (0 - 1.0)

χ An arbitrary multiplier ($\chi > 0$) of r_s used to account for such factors as senescence, stress, etc.

Basic subscripts

a,f,g	Air (at instrument height), foliage, ground surface
af	Air within foliage layer
ag	Air near the ground surface
↓,↑	Downwelling, upwelling
n	Net exchange (thermal infrared) between foliage and the ground
s	Sky (R_s) or saturation (e_s,q_s)
c	Canopy (ensemble of foliage elements) value for resistance to water vapor diffusion

Physical properties

C_p	Specific heat at constant pressure of dry air
k	von Karmon constant (0.4 used here)
K	Heat conductivity of the soil (assumed constant)
L	Latent heat of evaporation $L = f(T_a)$

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Balick, Lee K.
Inclusion of a simple vegetation layer in terrain temperature models for thermal infrared (IR) signature prediction : final report / by Lee K. Balick, Randy K. Scoggins, Lewis E. Link, Jr. (Environmental Laboratory, U.S. Army Engineer Waterways Experiment Station). -- Vicksburg, Miss. : The Station ; Springfield, Va. : available from NTIS, [1981].
34, [5] p. : ill. ; 27 cm. -- (Miscellaneous paper / U.S. Army Engineer Waterways Experiment Station ; EL-81-4)
Cover title.
"August 1981."
"Prepared for Headquarters, Department of the Army, under Project No. 4A762730AT42, Task A4, Work Unit 003, and Project No. 4A762719AT40, Task CO, Work Unit 006."
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TA7.W34m no.EL-81-4